III.D.3 An Investigation to Resolve the Interaction between Fuel Cell, Power Conditioning System and Application Load

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Objectives

- Conduct comprehensive transient spatio-temporal system modeling of a planar solid oxide fuel cell (PSOFC) based power conditioning system (PCS) on a low-cost Simulink and gPROMS platform, comprising the following subsystems: PSOFC, balance-of-plant (BOPS), power electronics (PES), and application loads (ALs), leading to reduced-order and computationally efficient PCS model.
- Resolve the interactions among PSOFC, BOPS, PES and ALs.
- Analyze the impact of electrical-feedback effects (e.g., load transients, load power factor, high- and low-frequency ripples) on the performance and durability of PSOFC.
- Optimize power-management control system for mitigation of electrical-feedback effects on PSOFC to enhance its life and performance.
- Conduct BOPS parametric optimization for optimal startup, steady-state, and transient performances.

Approach

- Developed the rigorous numerical model of the PSOFC PCS using
  - Comprehensive (2-D) and reduced-order (1-D) spatio-temporal PSOFC model developed using Embedded MATLAB functions that seamlessly integrate with Simulink;
  - Comprehensive BOPS model developed in gPROMS; reduced-order model being developed in Simulink;
  - Comprehensive (switching) and reduced-order (state-space averaged) PES models developed in Simulink and SimPower Systems;
  - Modeling of ALs in SimPowerSystems;
  - Glueless integration of PSOFC and PES and AL models in Simulink; integration of BOPS model in gPROMS with rest of the PCS Simulink models via gO:Simulink software. Once the reduced-order BOPS model in Simulink is completed, an all-Simulink software model will be available that can potentially be used for real-time simulation (RTS).

- Conduct detailed parametric studies on the PSOFC PCS to investigate the effects of variations of the air and fuel flow rates, operating temperature, load power factor and magnitude of low-frequency ripple on the PSOFC stack and the PCS as a whole. This work leads to a detailed database.
- Analyze the effects of load transients (e.g., no-load to full-load) on the residual thermal stresses inside the fuel cell using finite element analysis and estimate the probability of failure on a test PSOFC.
- Identify ways to mitigate the effects of single and multiple load transients and low- and high-frequency current ripples via
  - A current-injection based active-power filter for battery based power-management control system;
  - Choice of PES topologies and how they shape the PSOFC ripple current;
  - Studying the effects of variations in the power factor of the AL and the impact of load-current distortions due to nonlinear ALs on the PSOFC output current.

Accomplishments

- Developed a low-cost, transient, and spatio-temporal PSOFC PCS modeling platform with varying degree of details (i.e., comprehensive and reduced-order).
- Established a comprehensive database that gathers the effects of various electrical feedbacks on the PSOFC.
- Using a unique multi-organizational (UIC, Ceramatec, and ORNL) approach, demonstrated that certain load transients may develop electrically induced thermal stresses in a PSOFC, which may lead to higher probability of failure of the electrolyte of the PSOFC.
- Developed a highly efficient PES which will be used for experimental validation of modeling data by integrating with an experimental PSOFC stack.

Future Directions

- Realization of all-Simulink reduced-order PSOFC PCS model.
- Scoped validation of the electrical-feedback effects using an experimental PES (fabricated at UIC) and an experimental PSOFC stack (fabricated at Ceramatec).
- Development of power-management control strategies for PES and BOPS to enhance the performance and life of the PSOFC.

Introduction

A comprehensive model of the PSOFC PCS is being developed to meet the following objectives: i) to resolve PSOFC power system interactions and dynamics and develop design insights towards the achievement of reliable system configurations; ii) to enable interaction analysis, control, and optimization on a low-cost modeling platform; and iii) to potentially enable faster and real-time simulation for long-term reliability analysis.

A hierarchical modeling framework is being designed, based on the MATLAB/Simulink platform, which enables seamless integration of the subsystems to obtain a full-scale system model. The huge order (due to the bulky BOPS model) and very fast switching discontinuity (due to switching PES) of the system model are eliminated by creating accurate reduced-order models for each of the subsystems. The effects of various electrical feedbacks (such as different load transients, load power factor, current ripple), PES topology, and the battery size on the performance of the PSOFC are analyzed. A detailed thermal stress analysis is carried out to investigate the effect of load transients on the reliability of the PSOFC. A parametric database of feedback effects (using the PCS model) is created, which will provide design guidelines and help with system identification and optimal controller design for the PCS.

Approach

For accurate prediction of the effects of system interactions on the PSOFC, one needs to analyze the PSOFC internal parametric variations [1-6]. Because a purely temporal model of the SOFC (e.g., [7]) cannot predict the spatial dynamics, a spatio-temporal electro-thermo-chemical model of the PSOFC (in Simulink), which includes spatial discretizations of the cell, has been developed. This model is designed to accept required system inputs (reactant stream flow rates, compositions, temperatures, cell geometric parameters, and cell current) and to compute the corresponding spatially varying properties of a cell. As shown in Figure 1, a single 10 x 10 cm cross-flow SOFC was discretized using a 30 x 30 control volume grid, with each control volume approximated as having homogenous properties throughout. The outer 1 cm perimeter is treated as electrochemically inactive seal area, leaving a 64 cm^2 active cell area. Radiation boundaries will be applied to each exit stream boundary, while both reactant inlet faces are treated as adiabatic (insulated) but open (mass inflow) boundaries. Temperature is the primary transient variable, which will be integrated through time using the Euler explicit method.

We designed a comprehensive modeling framework. The system model comprises PSOFC, BOPS, PES, ALs, and the battery bank. The flow of various parameters among the subsystems is ensured to ascertain proper system interaction. The comprehensive model requires two low-cost software packages for implementation (MATLAB/Simulink including SimPowerSystem and gPROMS including gO:Simulink).

The bulky BOPS model with hundreds of components and subcomponents is much slower than the high-frequency switching model of the PES; hence, the BOPS model slows down the overall speed of simulation of the integrated PCS model. Therefore, to reduce the simulation time and to potentially enable fast RTS, we needed to develop a reduced-order PCS model devoid of switching discontinuity. This is obtained by averaging the switching states of the PES switching model, leading to a continuous model of the power electronics. The lower-order 1-D PSOFC model is derived by

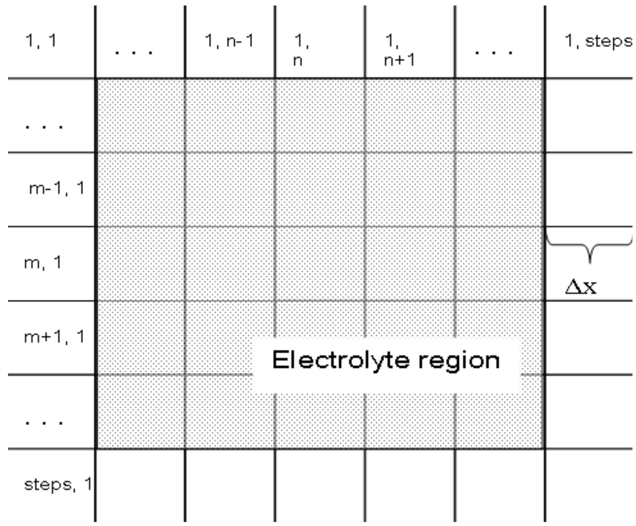

Figure 1. Spatial Homogenous Model for the PSOFC Providing Two-Dimensional Discretizations

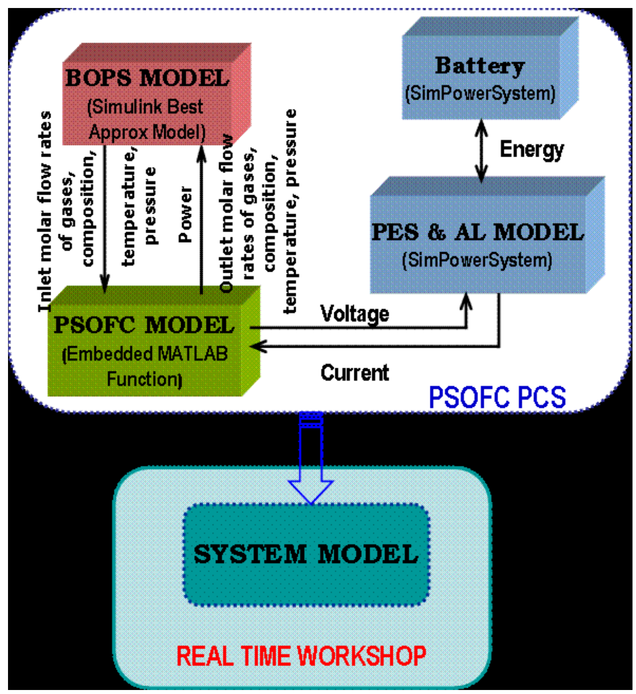

Figure 2. Reduced-Order Modeling Framework for PSOFC Based PCS, Developed in MATLAB/ Simulink Platform

reducing in one of the dimensions of the comprehensive 2-D model. Finally, the BOPS model is approximated using a multi-order polynomial approximation. The reduced-order PCS modeling framework, as shown in Figure 2, improves the simulation speed without compromising accuracy.

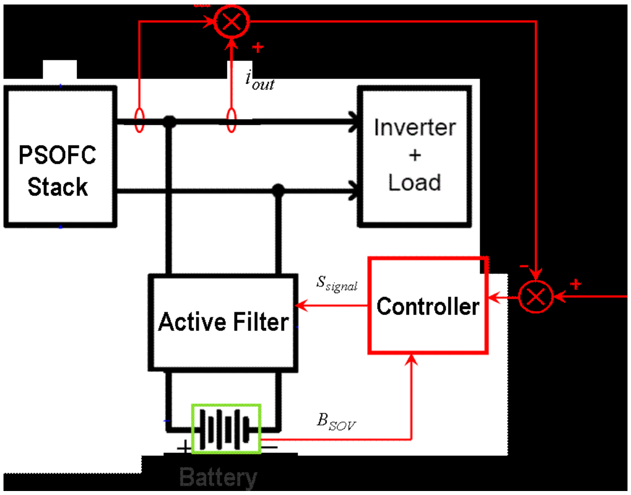

Figure 3. The Proposed Battery Management Controller

Figure 3 shows a battery based power-management control system to mitigate the effects of load transient on the PSOFC. The battery bank is connected at the stack output through an active filter. The components of the active filter are designed based on the high-frequency ripple limitations on the input and output currents and the output voltage. During a load transient, because the BOPS cannot provide the additional air and fuel instantaneously, the active filter, which is a boost-derived converter, supplies the excess load current. This required amount of current (i_{ref}^*) is computed based on the flow adjustment of the BOPS and the severity of the load transient. The difference between i_{ref}^* and the actual battery current i_{bat} is fed to the controller, which produces the switching signals for the active filter based on the state of the voltage of the battery, B_{SOV}. The controller gains for the active filter are designed and tuned using the AC equivalent model [9] of the filter.

A control scheme is proposed for the BOPS, which is integrated to the PES and the PSOFC stack [10]. A multilevel control approach is used in order to help improve the time response of the BOPS. The first level is determined by the air- and fuel-tank pressures. The objective of the fuel processing subsystem (FPS) and work recovery and air supply system (WRAS) is to keep the tank pressures at fixed values. Control strategies should guarantee that the fuel in the tank is never depleted and should ensure that no shut-down process is complete before proper levels of fuel in the tank are reached. Two additional control actions are implemented for the steam-methane reformer to regulate the exit composition and temperature of the reformate gases. The reformate temperature and composition of the steam-methane reformer are controlled using the inlet temperature and mass flow of the hot gases. The system-level optimization problem is that of minimizing the total cost of the system through its entire life cycle. It is formulated in terms of the capital cost of each subsystem and the total operation/control cost.

Results

We analyzed the effects of load transients on the performance and durability of the PSOFC. The drop in the output voltage of the stack due to the load transient [7, 8] is attributed to the enhanced polarization losses owing to a surge in the current density. Because the response of the BOPS is significantly slower than that of the PES/PSOFC stack, the input fuel flow rates of the stack will not change soon after the load transient. This leads to a sudden increase in fuel utilization inside the PSOFC stack to attain a new electrochemical steady-state condition.

Higher fuel utilization leads to increased rate of the exothermic reactions, which in turn increases the heat rate. This, added to the large response time of the BOPS (i.e., its inability to adjust the air and fuel flow rates instantaneously after the load transient), leads to a gradual increase in the fuel-cell temperature due to the higher thermal time constant of the PSOFC. This is demonstrated in Figure 4. Immediately after the load transient, the net change in the PSOFC mean temperature is minimal; however, at about 600 seconds after the transient, the PSOFC mean temperature reaches its peak. Figure 5 shows the temperature gradient inside the PSOFC corresponding to three separate time instants A, B, and C (shown in Figure 4). Owing to the temperature gradient, a tensile stress is developed at the interface of the electrolyte with the anode of the cell. (These data were calculated initially by ORNL without taking into account the residual stress. Work is in progress to recalculate these tensile stresses and the probability of failure.)

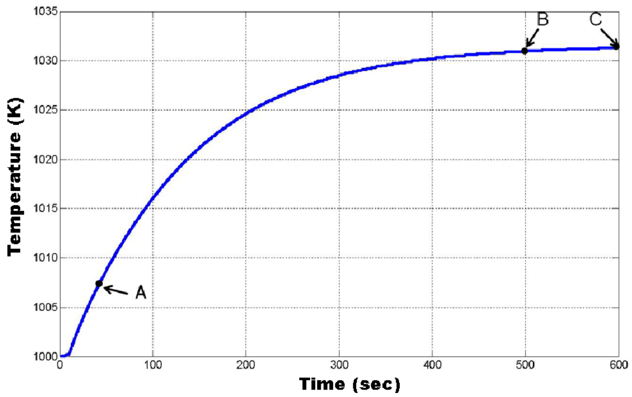

Figure 4. Variation of Mean PSOFC Temperature with Time. Three points, A (t = 50 s), B (t = 500 s) and C (t = 600 s) are chosen for analysis of stress inside the cell.

To investigate the effects of multiple load transients, we subject the PSOFC PCS to multiple short-duration loads in a fixed duration of 600 seconds. The duration of the load is kept fixed at 100 seconds. This type of load variation is attributed to a typical usage of microwave oven load. Temperature of the PSOFC increases with the number of load repetitions. This is because the frequency of the load transients is larger than the inverse of the PSOFC thermal time constant. Thus, multiple load transients can potentially affect the durability of the PSOFC.

The effect of load power factor on the hydrogen utilization and the cell voltage at a constant active output power to the utility is investigated. The fuel utilization increases at lower power factor. The variation in the hydrogen utilization increases as power factor is reduced. Thus, one needs to set the operating fuel utilization at a lower value to avoid the low-reactant condition in the cell; this reduces the efficiency of the cell.

With an increase in the ripple magnitude, the fuel utilization of the PSOFC increases; however, the cell efficiency decreases. In the PES, the loss in the circuit increases with increasing ripple magnitude due to an increased value of the current, thereby decreasing the efficiency of the system further. Therefore, the natural suggestion would be that the magnitude of the ripple should be reduced to achieve higher efficiency of the PSOFC and to reduce any unwanted increase in the fuel utilization. However, decreasing the current ripple requires higher values

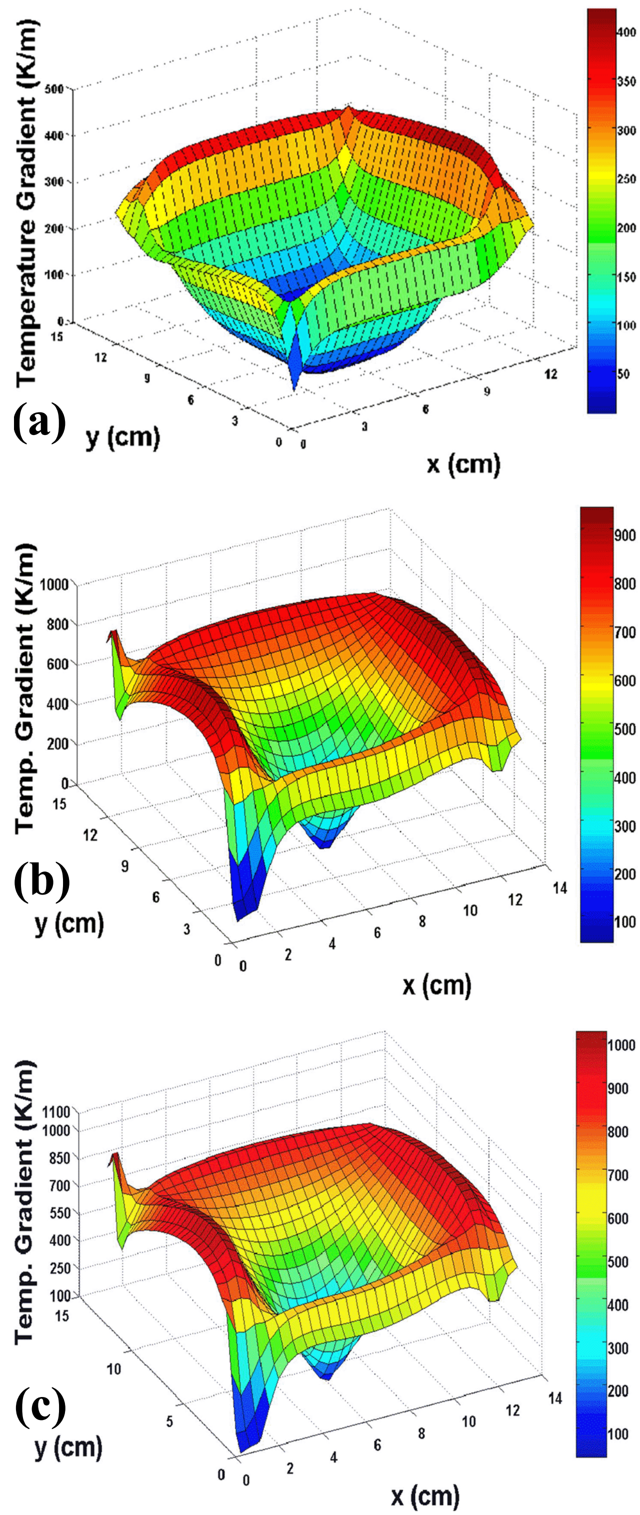

Figure 5. Temperature Gradient Inside the Cell at Instants A, B and C after the Load Transients (refer to Figure 4)

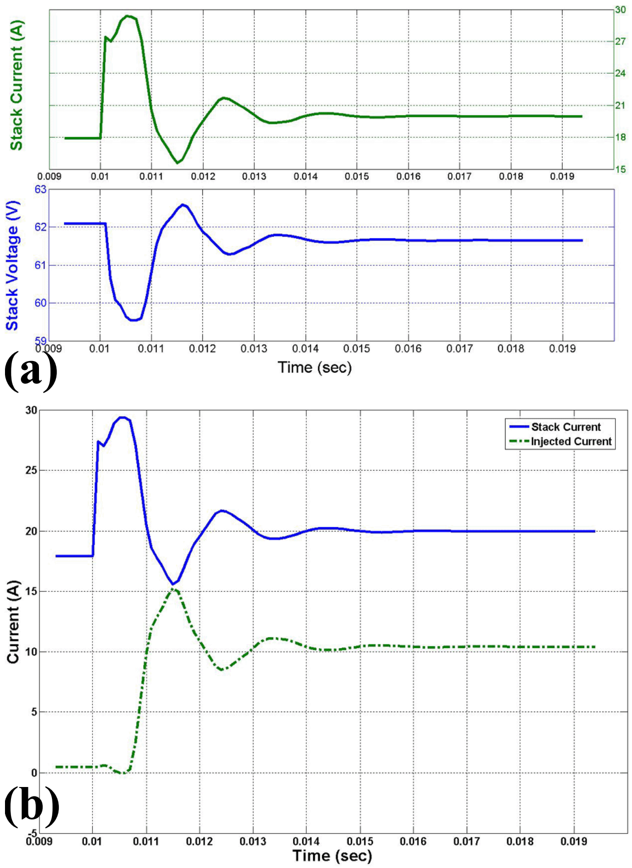

Figure 6. (a) Stack Current and Stack Voltage before and after the Load Transients; (b) Stack Current and Output Current of the Active Filter before and after the Load Transients

of the output electrolytic capacitor, or active-ripple-cancellation circuit, which increases the cost of the PES.

The dynamic optimum trajectories of the actual reformate tank pressure closely follow the optimum-pressure trajectory. The optimum tank pressure (i.e., in effect the system pressure) is a function of system demand [10, 11]. At high loads, the optimum pressure is higher because at low loads, both the stack and FPS efficiencies are higher and the increase in the pressure has a minor effect on the stack efficiency increment. On the other hand, the WRAS is less efficient at low loads and, therefore, the parasitic power due to the electrical motor at low loads increases as the system pressure increases. The dynamic trajectory of the methane flow rate into the reformer is the control variable for the reformate tank pressure. This mass flow is in fact regulated by a flow control valve. The rapid increase in the mass flow at 86,400 sec is due to the sudden change in the reference pressure, which produces an instantaneous error signal, which the controller tries to correct.

Finally, we investigate the effect of the battery buffering. As shown in Figure 6a, we subject the PCS to a load transient at time t=0.01 second. As a result, the stack output current increases to meet the new load demand. This increase in the stack current leads to a drop in the stack output voltage. Now, the required battery current i_{ref}^{*} is fed as a reference to the active filter controller shown in Figure 3. As illustrated in Figure 6b, the current output of the active filter, fed from the battery, increases to supply the excess load current, which in turn stabilizes the stack voltage close to its nominal value. Hydrogen utilization of the stack is maintained between 0.55 and 0.7.

Conclusions

The study conducted in the previous year gives detailed insight into the impacts on the PSOFC stack and the PSOFC power conditioning system of various electrical-feedback effects due to the power electronics and the application loads. This allows the determination of the required response time of the BOPS and power-buffering mechanism and control to avoid any degrading effect on the PSOFC. Our interaction analyses yield the following conclusions:

- A severe no-load to full-load transient increases the current density of the PSOFC immediately, which leads to a higher temperature inside the cell due to rapid exothermic reactions. The increase in the temperature increases the temperature gradient inside the cell, which in turn dictates the tensile stress on the PSOFC stack.
- Multiple load transients, with frequency of repetition higher than the inverse of the PSOFC thermal time constant, will be even more detrimental to the PSOFC durability, as compared to a single load transient.
- Apparently, the low-frequency ripple (e.g., 120 Hz ripple) current does not increase the PSOFC temperature even at high ripple magnitude. This is because the time period of the ripple is negligible as compared to the thermal time constant of the PSOFC. However, the higher the magnitude of the ripple current, the lower is the efficiency of the stack. Further, the impact of the

ripple current on the chemical stability of the electrodes and electrolytes needs to be investigated. This is a different mechanism of instability than that due to electrically induced temperature rise, as observed after load transients.

- Lower power factor of the load increases the fuel utilization of the stack due to higher circulating AC current in the circuit.

The optimization study leads to a system configuration which is able to meet all of the load requirements and system constraints. In particular, using reformate and air tanks as buffers between the BOPS and the PSOFC stack is shown to be an operational and cost-effective method which minimizes the transient effects on the SOFC stack due to changes in load.

Special Recognitions & Awards/Patents Issued

1. Dr. Mazumder presented the Keynote Lecture on fuel cell power electronics at the ASME Third International Conference on Fuel Cell Science, Engineering and Technology, held at Yipsilanti, Michigan, May 23 – 25, 2005.
2. A non-provisional patent (entitled "A novel efficient and reliable dc/ac converter for fuel cell power conditioning") was filed by the University of Illinois at Chicago (UIC).
3. Since the summer of 2004, a UIC student team comprising 10 undergraduate and graduate students has been working under the leadership of Prof. Mazumder on a prestigious International Fuel Cell Energy Challenge project sponsored by IEEE. This project has leveraged the fuel-cell knowledge gained as a part of the DOE Solid State Energy Conversion Alliance (SECA) work, leading to the design and the development of a 1-kW fuel-cell grid-connected inverter for residential power system. The UIC team has been selected as one of the 6 finalists. The final competition will be held in Colorado at the National Renewable Energy Laboratory test site in August.
4. Dr. Diego Rancruel, who was one of the Virginia Tech graduate students working on the DOE SECA project, has joined General Electric Energy and Power Generation Technology as a Lead Engineer for their New Product Introduction Division.

FY 2005 Publications/Presentations

1. S. Pradhan, S.K. Mazumder, J. Hartvigsen, M. von Spakovsky, "Effects of electrical feedbacks on the reliability of the planar solid-oxide fuel cell (PSOFC) power conditioning system", accepted for publication, Fuel Cell Seminar, 2005.
2. S.K. Mazumder, S. Pradhan, J. Hartvigsen, M. von Spakovsky, and D. Rancruel, "Effects of battery buffering and inverter modulation on the post load-transient performance of planar solid-oxide fuel cell", *IEEE Transactions on Energy Conversion*, in press for publication, 2005.
3. S.K. Mazumder, *Fuel Cell Power-Conditioning System*, Editor S.K. Basu, Kluwer Academic Publishers, expected year of publication: December 2005.
4. S.K. Mazumder, S. Pradhan, K. Acharya, J. Hartvigsen, M. von Spakovsky, and C. Haynes, "Load-transient mitigation techniques for solid-oxide fuel cell (SOFC) power-conditioning system", *Proceedings of the IEEE Telecommunications Energy Conference*, pp. 174-181, 2004.
5. S.K. Mazumder, K. Acharya, S. Pradhan, J. Hartvigsen, M. von Spakovsky, and C. Haynes, "Energy buffering techniques for load transient mitigation of solid-oxide fuel cell (SOFC) power conditioning system (PCS)", *Proceedings of the IEEE Power Electronics Specialists Conference*, vol. 6, pp. 4749-4754, 2004.
6. D.F. Rancruel, M.R. von Spakovsky, "Development and application of a dynamic decomposition strategy for the optimal synthesis/design and operational/ control of a SOFC based APU under transient conditions", *International Mechanical Engineering Congress and Exposition – IMECE'2005*, submitted for publication, ASME Paper No. IMECE2005-82986, 2005.
7. D.F. Rancruel, M.R. von Spakovsky, "A decomposition strategy based on thermoeconomic isolation applied to the optimal synthesis/design and operation of an advanced tactical aircraft system," *Energy: The International Journal*, Elsevier, 2004, accepted for publication.

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11. D.F. Rancruel, M.R. von Spakovsky, "Development and application of a dynamic decomposition strategy for the optimal synthesis/design and operational/ control of a SOFC based APU under transient conditions", *International Mechanical Engineering Congress and Exposition, IMECE'2005*, submitted for publication, ASME Paper No. IMECE2005-82986.